

Development and Testing of a Vehicle Collision Avoidance System Based on GPS and Wireless Networks for Open-Pit Mines

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ABSTRACT

A vehicle proximity warning - collision avoidance system is being developed using GPS and wireless local area networks to improve safety of off-highway trucks in open pit mines. After two an a half years of research, software development, and laboratory testing, field tests were carried out at operating limestone quarries and open pit mining operations to evaluate GPS accuracy and overall system effectiveness under rugged operating conditions. This article describes the progress made on this NIOSH funded project and discusses the GPS accuracy tests and overall system tests that were carried out during the year 2001 at the Colorado School of Mines Survey Field and at the Morenci open pit copper mine in Arizona.

Keywords: GPS, Advanced Mining, Virtual Reality, Wireless Networks, Proximity Warning.

1 INTRODUCTION

A proximity warning – collision avoidance system based on the Global Positioning System (GPS), wireless networks, and 3D graphics technology is being developed at the Colorado School of Mines in order to reduce powered haulage equipment accidentence in open pit mining operations. A brief description of the system development background and testing results of the GPS accuracy level achieved are presented in this paper. More information on the development, computer code, and applicability of the system is described in Nieto, (2001).

Powered haulage equipment used in mining and construction operations are involved in hundreds of accidents resulting in a significant number of fatal accidents each year. The U.S. Department of Labor, Occupational Safety and Health Administration reported that the powered haulage accidents caused an average of 23 deaths a year for the period of 1992-1999 (see Camm, 2000; Ruff, 2000). These accidents happened from situations where a truck backs up over a smaller vehicle or the truck rolls over the edge of a dumpsite or a ramp. In both types of accidents, the truck operator inability to see dangers in the truck's blind spots, behind and to the side of the truck, has been a major contributing factor. These accidents resulted in the loss of significant number of human lives and millions of dollars in equipment and productivity cost.

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2 SYSTEM DESCRIPTION

The proximity warning – collision avoidance system described in this paper involves the use of three different state-of-the-art technologies in an attempt to prevent accidents resulting from powered haulage equipment: the GPS, the wireless network system, and a 3D graphical engine interface (see Figure 1).

All these technologies were combined in a real-time system named “VirtualMine” (see Dagdelen and Nieto).

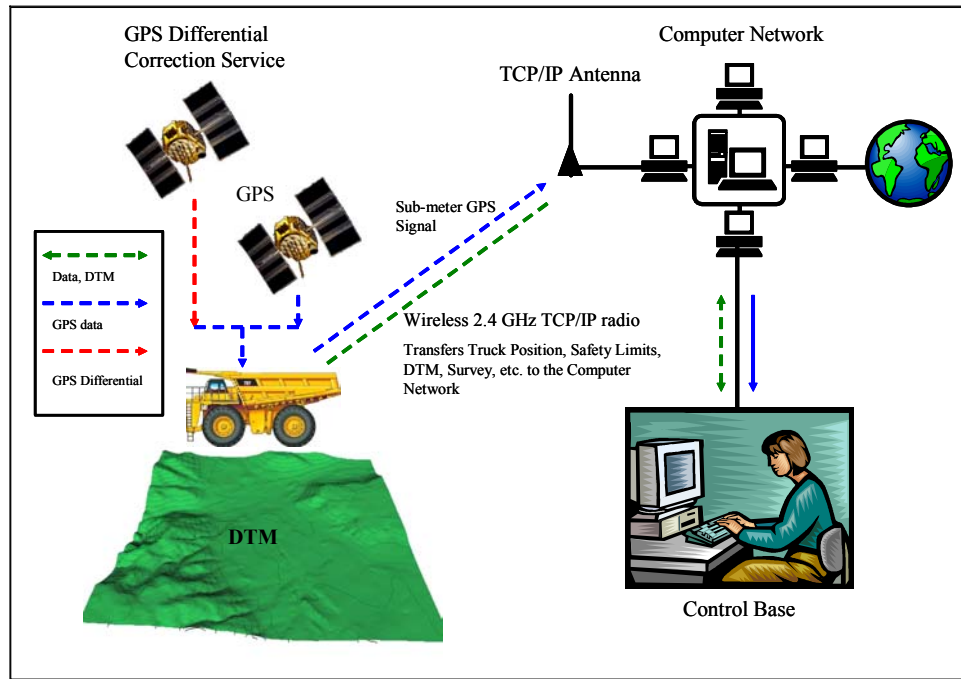


Figure 1. Schematic representation of the configuration used to monitor a remote truck from the central office.

The developed system envisions the following goals:

- The system should be capable of tracking the vehicle with respect to the edge of a dumpsite as well as to other vehicles in real-time, warning the driver of close proximity or collision.
- The system should be user friendly and easy to understand by the driver using simple and representative computer graphics.
- The mine vehicle will be integrated with a screen monitor linked to the system's computer to give the driver a real-time picture of the vehicle with respect to its surroundings.
- The system should be sub-meter accurate regarding its position with respect to the safety berm and with respect to the position of other vehicles.
- The system should be capable of 3D contour mapping on demand, in order to monitor a vehicle's position with respect to the mine's geometry.
- The vehicle's position should be shared among all the operating vehicles using a wireless-radio network. This system should further be able to update the mine's geometry on demand, based on remote vehicle's coordinates.
- The system must be tested in a mining operation to check for its operability, effectiveness, and operator acceptance.

2.1 GPS and Computer Hardware System

The GPS hardware used in this system is configured to output device coordinates in ASCII NMEA (Anon, 2000) code and connected to a PC computer through a serial port.

The system can operate using differential GPS or RTK-GPS receivers as long as they are NMEA compatible. The RTK-GPS receiver used for testing was a Trimble 4400, which was hooked to a 900 MHz TCP/IP-upgraded Trimble radio. When using the RTK-GPS system a base station is established to broadcast coordinate corrections to the GPS unit installed in the truck. When the system was configured for differential GPS --using a correction service from Omnistar-- the Trimble AG-GPS 132 receiver was used. Both GPS receivers are manufactured by Trimble and currently marketed by Caterpillar.

A PC-computer and display system (from Xplore Inc.) was used as an onboard computer and graphics display unit. This display unit was selected among other similar technologies for its embedded touch screen and rugged features. The Xplore PC-Screen is shown in Figure 2 (left). The Xplore computer unit is a Pentium-III PC based on windows 98 and runs at 500 MHz, this model is a mountable unit that could be installed in any vehicle. It has an internal PC card slot, which could be used eventually to install an internal 802.11b wireless radio card (during testing the radio cards were connected externally using a USB adaptor).

In Figure 2, the picture on the left shows the installed computer system on the truck's cabin. The picture in the right shows the Caterpillar 793 truck and a Chevy Pickup, both mounted with the VirtualMine system at the Morenci Mine in Arizona. To increase range when testing was carried out, radios were connected to one watt amplifiers which were in turn connected to omni-directional antennas as shown in the picture.



Figure 2. (left) A picture showing the installed rugged flat panel computer on a CAT 793 truck. (Right) a picture showing Orinoco wireless radio antennas mounted on a truck and a pick-up vehicle.

2.2 Wireless Communication Network System

The wireless network system used is TCP/IP compatible and it can use both, the TCP/IP upgraded Trimcomm-900 radios from Trimble or 802.11b radio card (Molta, 1999; and Rysavy 1999). The system sends position and survey information to network-enabled trucks and to the base station using the 802.11b wireless network. This information is based on xyz packets which are used to map on-demand the mine site and to pinpoint truck location within the mine model.

The range of an 802.11b system using standard radio cards is in the average of couple of hundred meters; however using one watt amplifiers connected to an omni directional antenna, the range has increased to approximately two to three kilometers depending of line of sight conditions.

The base station receives the data being broadcasted from the vehicle through an access-point connected to a computer that is on the main wired network. If this network is routed to the internet, the monitoring of equipment over the updated terrain map could be carried out from any computer connected on the internet using IP addresses. The same IP process is true when sending position and terrain information from vehicle to vehicle in a peer-to-peer TCP/IP scheme. The wireless capability of the system also offers real-time database management in order to update operative data (grade, tonnage, truck maintenance, road condition, etc.)

2.3 Virtual Mine Software

Development of the Virtual Mine Software and its visual graphical interface was carried out using Visual Basic language [20] and Virtual Reality Modeling Language (VRML) (See Ames, 1997). The software being developed is in charge of several functions:

- Reading NMEA code from the GPS unit through a serial port converting it from geodetic coordinates (Latitude and Longitude) into UTM coordinates (Doyle, 1997; Grafarend, 1995; Herzfeld, 1999; Williams, 1995).
- Transformation of DXF mine maps into 3D VRML maps.
- Visualization of 3D mine maps.
- Position tracking of local and remote vehicles in real time.
- Generation of 3D mine maps on-demand.
- Handling of the TCP/IP wireless communication protocol to transmit and receive positional and terrain data from remote vehicles.

As mentioned before VRML was chosen as the graphic engine to construct a 3D interface to be used in the system. Thus, and in order to be compatible with the graphics format, a Visual Basic routine was written to translate DXF files (in this case contour lines in 3D poly-lines format) into VRML 3D lines. By doing this, a mine map created in DXF could now be visualized in the onboard computer in 3D view, which can be dynamically rendered in real time, instead of using 2D graphics. Using the 3D system environment the system generates a 3D truck model, which is dynamically positioned on the map based on the xyz coordinates coming from the GPS unit. The system then monitors the 3D truck position with respect to the mine map as shown in Figure 3.

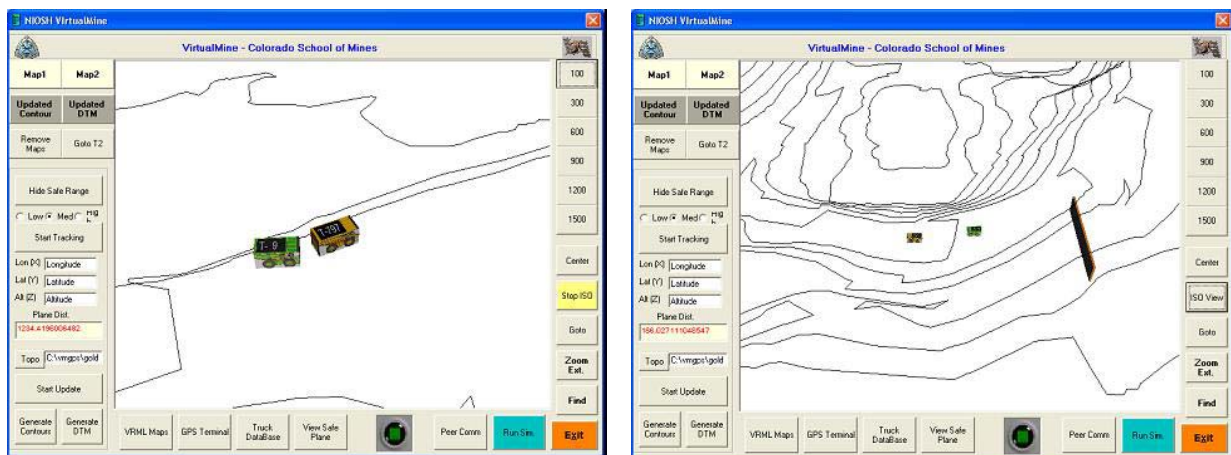


Figure 3. 3D contour map showing two trucks being monitored by the proximity warning system.

The proximity warning system generates a 3D spherical bubble surrounding the truck indicating the safety zone around the vehicle. Then the system monitors the 3D truck position and its distance with respect to a virtual safety berm represented by a plane. If the truck approaches or crosses this plane, a series of alarms are triggered to warn the operator. See Figure 4.

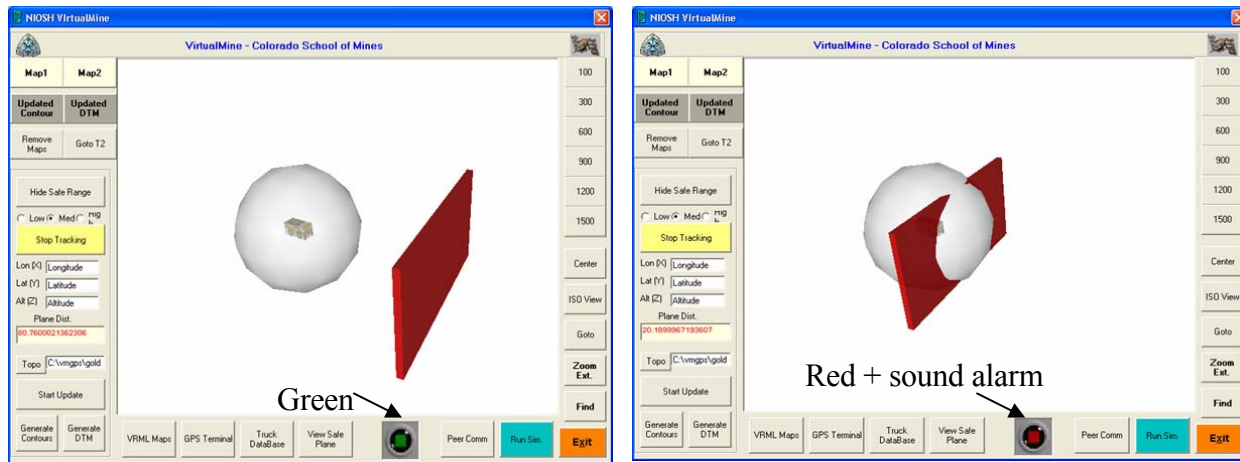


Figure 4. Series of snapshots showing 3D models of the truck and its safety bubble, the picture here shows the truck intersecting a safety berm (represented by a plane) and warning the truck operator.

It is envisioned that if another vehicle comes within the safety sphere of a given truck the system would warn the operator of both trucks of impending danger. The VirtualMine system also has the capability to update the contour map of a given section of the mine on-demand using xyz information coming from actual truck locations as well as the location of other vehicles such as dozers. This is accomplished by saving the xyz coordinates received through the wireless network coming from enabled remote vehicles. This xyz data is then used to generate a topo-grid file that is automatically contoured and displayed on-demand in the onboard computer.

3 GPS ACCURACY TESTS

In order to assess the quality of the GPS results during the proximity warning exercises, accuracy and precision tests were performed at the Colorado School of Mines (CSM) survey field.

Accuracy tests focused on measuring the departure of GPS measurements from the true value; precision tests on the other hand, measured the repeatability of the data. The difference between accuracy and precision is known as "bias" or "systematic error", for example, taking large amounts of data will improve the precision of a sample mean but will not remove its systematic error.

3.1 Accuracy Tests

The coordinates calculated by the GPS receivers were compared to a known surveyed point at CSM survey field known as the Gaby point. The UTM-WGS84 coordinates of this point are: Easting 481082.353, Northing 4398932.119, and Elevation 1811.83248. Equivalent Latitude is 39° 44' 24.27265" N, and Longitude is 105° 13' 14.83589" W.

The same Trimble-4400 and the Trimble-AG132 GPS units that were used for the proximity warning exercises were used for the GPS accuracy tests. The accuracy test for the 4400 receiver consisted in measuring results based on reading satellite carrier phase signals L1/L2. The accuracy test for the AG132 receiver measured results based on code phase signal using differential correction.

The differential correction signal unit was acquired in real time using the differential correction service from Omnistar (see Hollerich, 1998). The accuracy expected from Omnistar depends on the quality of the GPS receiver used; that is, a standard class GPS will give larger semi-random results relative to the true position than a "commercial quality" receiver. The better commercial GPS receivers can achieve horizontal errors of less than a half-meter for 67 to 73% of the time, less than a meter 95 to 97% of the time and less than 1.5 meters 99% of the time. Vertical error will be 2 to 2.5 times greater than the horizontal error. The expected standard deviation of the error acquired using differential correction has a standard deviation of approximately 0.5 meters.

The Omnistar Differential service consists of geostationary satellites that broadcast differential correction signals to specific zones on Earth. Omnistar has ten permanent base stations in the US and one in Mexico. These eleven stations track all GPS satellites and compute corrections. The corrections are sent to a network control center located in Houston via wired networks. At the control center, these messages are checked and sent to a satellite transponder. This occurs approximately every 2 seconds. A packet will contain the latest corrections from each of the 11 base stations as explained by Huff, 1995.

The accuracy test carried out at the CSM survey field consisted of precisely positioning the GPS antenna over the "Gaby" point to log and compare the coordinates generated by the GPS receiver.

Accuracy tests using the AG132 and 4400 GPS receivers from Trimble were carried out at 10:00 a.m., 4:00 p.m., and 1:00 a.m. to check for GPS accuracy based on different times and consequently based on different Dilution of Precision (DOP) factors (Parkinson, 1996; and Thompson, 1998).

A major factor in determining positional accuracy is the alignment, or geometry, of the group of satellites (constellation) from which signals are being received. The geometry of the constellation is evaluated for several factors, all of which fall into the category of Dilution of Precision, or DOP.

DOP is an indicator of the quality of the geometry of the satellite constellation. A computed position can vary depending on which satellites are used for the measurement. Different satellite geometries can magnify or reduce the errors described above. A greater angle between the satellites provides a better measurement. A higher DOP indicates poor satellite geometry and an inferior measurement configuration.

Accuracy tests using the AG132 GPS receiver, that uses differential correction, under an average DOP of 2.07, based on all collected samples, averaged a bias of 0.304 m. Easting, 0.734 m. Northing and a vector departure of 0.811 m. in relation to the surveyed Gaby point. Elevation bias using all the samples was 5.46 m. with a standard deviation of 0.41 m.

The 4400 GPS receiver, which uses L1/L2 carrier phase readings under an averaged DOP of 2.07, based on all collected samples, averaged a precision of 1.398 m. Easting, 1.714 m. Northing, and a vector departure of 1.92 m. in relation to the surveyed Gaby point. Elevation bias using all the samples was 32.9 m. with a standard deviation of 3.85 m.

Accuracy tests indicated that DOP impacts more significantly the 4400 receiver than the AG132 receiver due to the fact that the 4400 readings were based solely on reading the L1/L2 carrier phase directly from the GPS satellite signal without differential correction. The Differential GPS AG132 was not impacted by the DOP. In fact, its accuracy significantly improved due to the atmospheric conditions present during the 1:00 a.m. test.

The DOP was estimated according to the geographical location where the test was carried out using DOP tables generated from an online software package located at the web site: gibs.leipzig.ifag.de. The table presented visibility of satellites in Golden, Colorado on November, 11, 2001 from 0 to 24 hrs.

The positions acquired by GPS receivers 4400 and AG132 with respect to the Gaby point are given in Table 1, results for 4400 and AG132 at Nov 11th during the morning and afternoon are plotted in a scatter gram, as shown in Figure 5.

Table 1: Summary of results from the accuracy test

Time	DOP	Samples		Gaby Point UTM		4400 bias with respect to Gaby			AG132 bias with respect to Gaby		
				Easting	Northing	Easting	Northing	Vector	Easting	Northing	Vector
		4400	AG132	m		m			m		
10 AM	2.0	445	304	481082.353	4398932.119	1.46	1.33	1.98	0.40	0.45	0.61
4 PM	1.9	1008	1784	481082.353	4398932.119	0.76	2.25	2.39	0.30	0.89	0.96
1 AM	2.3	1080	341	481082.353	4398932.119	1.96	1.37	2.40	0.09	0.17	0.20
Total	2.07	5853	2429	481082.353	4398932.119	1.40	1.71	2.33	0.30	0.73	0.81

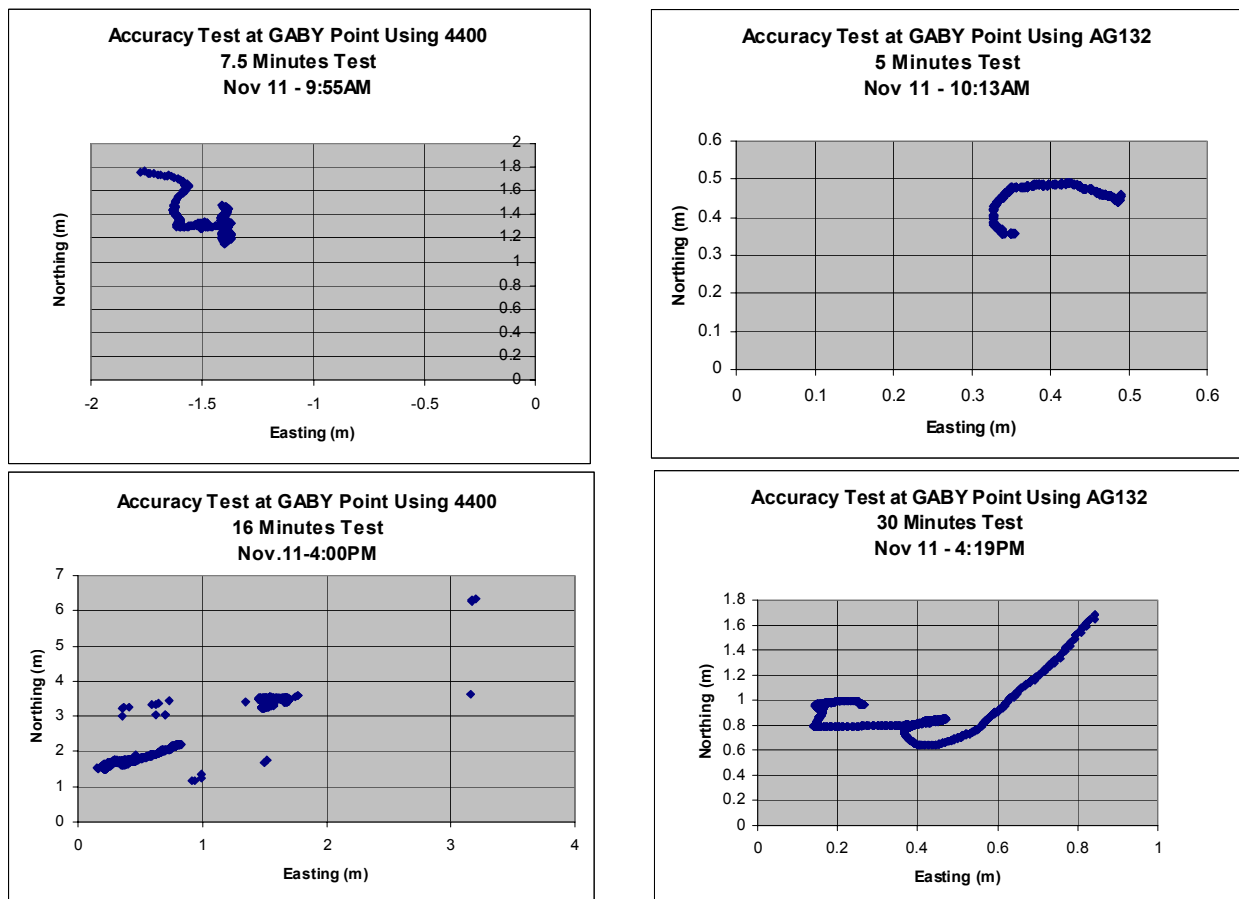


Figure 5. GPS Accuracy test at CSM (Gaby point) using the 4400 receiver (left) and the AG132 receiver (right).

3.2 Proximity and Precision Tests

Proximity tests consisted of repeatedly checking the vehicle's GPS position with respect to a known geometry in the field and its equivalent digital map loaded in the system.

The geometry used for the test was a regular grid of 6 x 24 meters, defined by square units of 2 x 2 meters. The grid was physically marked at the CSM survey field (see Figure 6) based on two known UTM points.

Point 0, 0: Easting 481094.48 m, Northing 4398935.22 m, and Elevation 1811.18 Point 0, 24: Easting 481083.52 m, Northing 4398957.40 m, and Elevation 1811.18.

The computer graphic grid was generated using AutoCAD and then transformed into the VRML format using one of VirtualMine transformation routines. Once the grid was loaded into the computer system, the virtual safety berm was positioned at line zero, emulating the edge of the dumping point, see Figure 7.

The vehicle was equipped with the AG132 Differential GPS receiver and positioned within the grid on repeated occasions during a one-week period to check the consistency of its reported position with respect to the computer grid. Positions of the truck as reported by the GPS receiver were logged and photo-captured at different distances in relation to the line (0,0) in order to be compared to its equivalent real grid position, as seen in Figure 6.

The 3D model of the vehicle used in the system was modified to match the dimensions of the Jeep Cherokee truck used during this test. The dimensions used to simulate the vehicle within the system were 4.4 x 1.7 x 1.7 meters. Dimensioning the model of the vehicle to the dimensions of the real vehicle was performed in order to be consistent with the position of the GPS antenna on both the model and the real vehicle, since in both cases the GPS antenna is located at the center of the truck. The GPS antenna was mounted on the jeep and positioned at its center (2.2 x 0.85 m) which is consistent with the position of the antenna in its equivalent 3D model. Note that GPS coordinates reported in the computer system are based on the position of the GPS antenna.

The following series illustrations show how the precision test was carried out at the survey field. The pictures show the position of the vehicle as seen on the computer screen and at the actual survey field, at an interval distance of 8 meters to the edge of the dumping point.

Table 2, is the tabulation of results obtained from the precision test. Last column (Biased) is the offset distance of the truck reported by the GPS receiver with respect to the real position on the surveyed grid.

Table 2: Position of vehicle with respect to grid, (Coordinates are based on the 0, 0 grid point).

Test ID	DOP	GPS Easting	GPS Northing	Grid Truck	GPS Grid Truck Position	Biased
Nov11-01	1.9	481094.94	4398943.51	7.8, 3.6	8.3, 3.0	0.5, 0.6
Nov11-01	1.9	481096.61	4398939.42	4.2, 3.8	3.8, 3.1	0.4, 0.7
Nov14-01	2.0	481096.58	4398939.48	8.0, 3.0	8.4, 3.1	0.4, 0.1
Nov14-01	2.0	481094.81	4398943.21	4.0, 3.0	4.4, 2.7	0.4, 0.3
Nov15-01	2.3	481096.35	4398938.68	4.0, 3.0	3.9, 3.5	0.1, 0.5
Nov15-01	2.3	481094.69	4398942.09	8.0, 3.0	7.8, 3.7	0.2, 0.7
Nov15-01	2.3	481093.19	4398945.59	12.0, 3.0	11.5, 3.8	0.5, 0.8

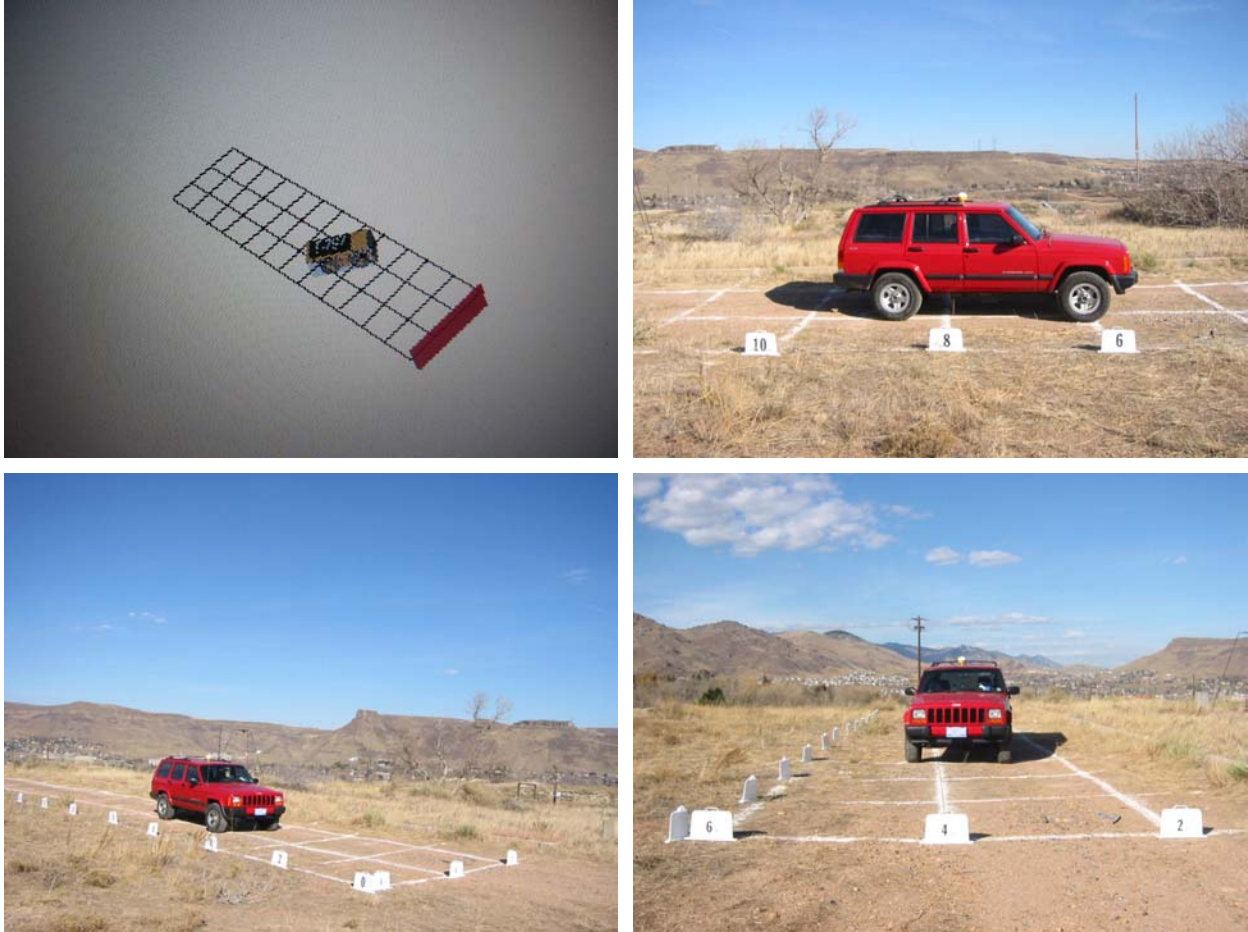


Figure 6. Precision test carried out at the CSM survey field, 8 meters distance to edge of dumping point. The grid is physically defined at the survey field. The equivalent vehicle and grid model as seen in the computer screen are shown in top-left picture.

The consistency of the distance between the vehicle and the dumping point as reported by the GPS receiver was tested in order to check the system proximity warning capability in relation to the GPS receiver. The safety berm represented by the 3D plane was positioned at line zero on the grid, as seen in Figure 7.

Test results show an average accuracy of 2.3 meters in relation to a known point using the 4400 GPS-receiver (L1/L2 carrier phase). On the other hand the system achieved sub-meter accuracy with an average error of 0.8 meters when using the AG132 Differential GPS-receiver (L1 code phase).

Tests also indicated that precision with respect to a given geometry is consistent. The system was able to pinpoint the vehicle over the 24x6 grid with sub-meter accuracy using the AG132 GPS-receiver and Omnistar differential correction.

In addition, the system was tested for close proximity to a dumping point, using the grid as a reference and positioning the safety berm at coordinates (0, 3) of the grid. This test was carried out using a safety sphere radius of 5 meters, see Figure 7.

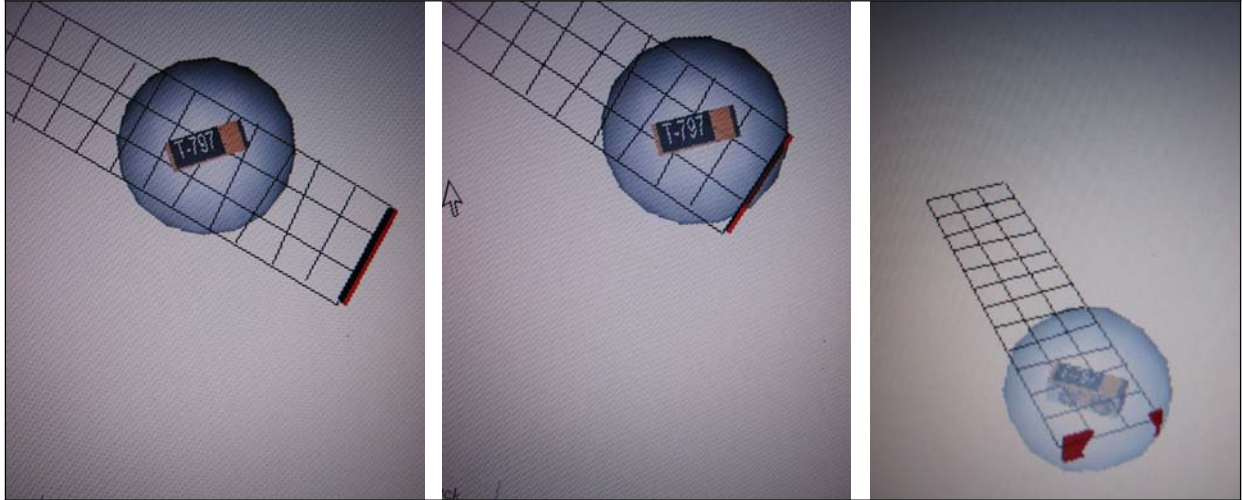


Figure 7. Proximity warning test with respect to the edge of dump site using safety sphere of 5 meters radius.

4 FIELD TESTS

Various tests were carried at the Morenci Open Pit copper mine, Morenci, AZ to check the applicability of the system. The descriptions of these tests are given below:

4.1 Vehicle Tracking and On-Demand Contouring

The first task after instrumentation was to test VirtualMine tracking and contouring capabilities in real-time. In order to run this task, VirtualMine was installed into a pickup truck emulating a CAT 797 mine truck, as described in Nieto, 2001.

In order to run this test in the field (Morenci Mine), the first step was to import Morenci topography data into the system. Morenci topo map is based in local coordinates, thus a transformation to UTM WS-84 was required. Once the topography data was transformed into UTM WS-84 coordinates, a portion of the mine was translated to VRML format and then compared to the actual location of the truck to check for GPS/Map consistency. The next stage was to drive into the main pit, to collect new survey data as well as to confirm GPS positioning and Map geometry.

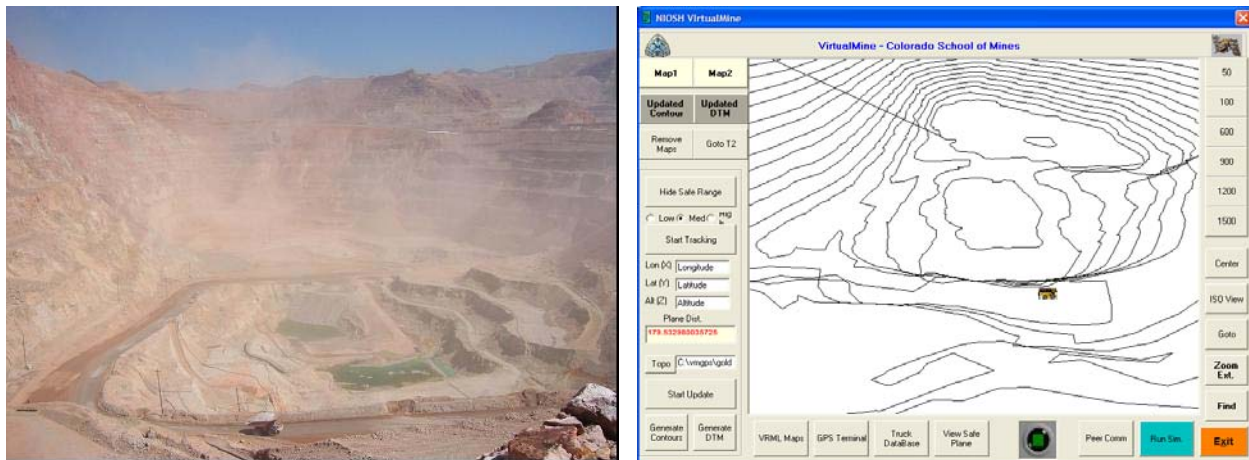


Figure 8. (Left) Picture of the main pit at Morenci, (right) Virtual equivalent of the main pit at Morenci as seen in VirtualMine

This task was performed successfully, the truck position was accurate with respect to the 3D map used, and the generation of contour lines was carried out effortlessly. The driver could see its own position with respect to the mine map and the system was able to update the pit contour map in real-time, while the truck was moving within the pit. In Figure 8, one can see the real pit at Morenci and the equivalent 3D contour map as seen through the VirtualMine interface. Notice the location of the CAT 793 truck in both pictures.

The proximity warning routine implemented in VirtualMine was also tested; the approach followed was to make the system to broadcast the GPS location of the vehicle to a nearby vehicle, using the TCP/IP wireless network. The system uses these coordinates to display both vehicles (local and remote) on the onboard computer screen. Next task at Morenci was to carry out the proximity warning system tests between two vehicles.

To perform the vehicle proximity tests at Morenci the VirtualMine system had to be installed in CAT 793 and in a pickup truck. Once the system was activated and the GPS signal was received, the next step was to activate the communication system using the peer-to-peer interface. For example, the Figure 3 shows the location of the trucks on the computer screen immediately after the TCP/IP connection is established at the Morenci Mine.



Figure 9. Picture taken at Morenci during the proximity warning test.

Proximity warning system was tested at Morenci with promising results as shown in Figure 9. The screen is indicating that the remote vehicle (in this case the truck) is touching the safety bubble, warning the driver of a close proximity.

Parallel to Morenci tests a series of field tests were carried out at Portland Quarry of Holnam in Portland, Colorado to check the accuracy of VirtualMine. The system proved to be consistent regarding the truck's real position with respect to the edge of the haul road and the system calculated GPS-position with respect to the mine map previously loaded in the system.

5 CONCLUSIONS

Fatal accidents related to dumping tasks and vehicle collisions are indeed occurring at open pit mines. The VirtualMine system being developed in this project could help in improving safety in open pit mines and could reduce significantly a number of these accidents.

The system tests carried out survey fields and in actual mining operations such as the Morenci mine in Morenci, Arizona, indicated that "VirtualMine", is a system that could be used as a vehicle tracking, proximity and collision warning system. However, the system being developed has to rigorously be tested at working sites to check its reliability and effectiveness.

Further research is recommended focused in developing a more reliable system for potential applications in expert dispatching systems for shovel operation, real-time mining control and the development of a friendlier working interface for truck operators.

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